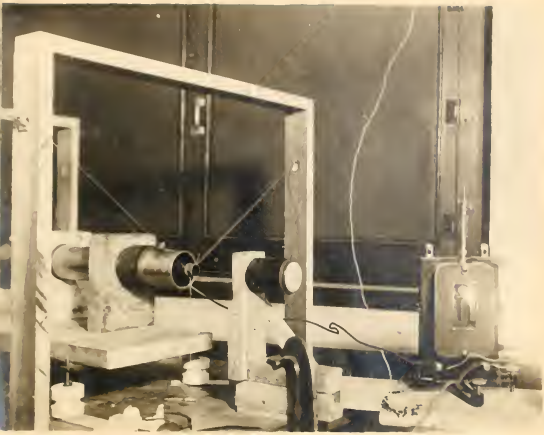

THE INFLUENCE OF DENSITY OF GAS ON THE FORMATION OF CORONA

Dissertation

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By

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1. Introduction.

This paper describes the results of a series of experiments on the effects of pressure, temperature, density of gas and size of conductor on the formation of corona. The study of the effect of pressure and temperature on corona forming voltage was begun by Ryan in 1904. The study was again taken up in 1909 by Watson. In 1910 Dr. Whitehead began an investigation of the corona and the work given here is largely an extension of that in the second of his series of papers on "The Electric Strength of Air". Peek has also devoted some study to these phases of the corona problem. All the observers mentioned used alternating current except Watson who worked with direct current.

The purpose of the present work has been the extension of the earlier investigations both as to range of pressure and size of conductor and also to obtain further information on the influence of temperature. Some observations were also made with carbon dioxide as the gas surrounding the conductor instead of air to see what part, if any, is played by the density of the gas.

The larger part of the work is the study of variation

of critical, or corona forming, intensity with pressure. For this work conductors varying from .036 to .950 cm in diameter were used, and the pressure was varied from 2 to 110 cm of mercury.

2. Review of Previous Work on Pressure and Temperature.

This review is confined largely to the investigations on variation of critical intensity with pressure and temperature. Some other points, however, have such an intimate relation to these variations or at least to a study of them that they will be mentioned.

It was shown by Ryan[1] that for the one size of conductor which he used the critical intensity is a linear function of the pressure from 40 to 90 cm of mercury. A similar relation was shown to hold for variations with temperature between 21 and 93°C.

Watson published a set of experiments[2] in 1909 showing a linear relation between pressure and critical intensity for the case of direct currents. His range of pressures was from 360 to 760 cm of mercury and in size

[1] Ryan, Conductivity of the Atmosphere at High Voltages. A. I. E. E. 23, 1904.

[2] Electrician. Vol. 63, 1909.

of conductors from .07 to .95 cm. He also gave curves showing the amount of current drawn.

In Dr. Whitehead's papers numerous curves were given showing a linear relation between critical intensity and pressure from 38 to 100 cm. The conductors used ranged in diameter from .122 to .475 cm. Some experiments were also made showing a linear relation between critical intensity and temperature. Only one size of conductor was used. The range of temperature was from 8 to 41°C.

It was further shown that:

The critical intensity is independent of free ionization, moisture content and velocity of the air.

The visual critical intensity is identical with that determined by an electroscope.

The critical intensity for clean round conductors for a pressure of 76 cm and temperature of 20° may be expressed by a formula of the form:

$$g = A + \frac{B}{\sqrt{D}} , \qquad (1)$$

where A and B are constants and D is the diameter of the conductor. This formula is discussed in a later paragraph.

Peek[3] has given the results of a set of experiments on

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[3] Peek. The Law of Corona. A.I.E.E. 31, 1912.

variations of critical intensity with temperature showing practically a linear law between -20 and +140°C. He has also given a general formula covering the variations of critical intensity with change of temperature and pressure for a tube and concentric conductor as follows:

$$g = 31\,\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right) \qquad (2)$$

where g is the critical intensity in kilo volts per cm, r is the radius of conductor and

$$\delta = \frac{3.92\ p}{273 + t},$$

p being the pressure in cm of mercury and t the temperature centigrade. So far as can be found the only statements he has given concerning the influence of pressure on the variation of critical intensity is a curve[4] giving observations on a 2.54 cm conductor for pressures from 2 to 65 cm and a table of values of δ and corresponding values of g in closing the discussion of his 1912 paper[5]. No description of his methods was given.

The observations of which the results are given in this paper were made in the spring of 1912 before some of Peek's work was published. It appears, however, that there is still a lack of sufficiently extensive data on variation

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[4] Peek: Nature of Corona. Gen. Elec. Review, Dec. 1912.

[5] Peek: Proc. A. I. E. E. Nov. 1912.

of critical corona intensity with pressure and size of conductor.

3. Apparatus and Equipment.

For the pressure measurements a 20 cm iron tube about 90 cm in length was used. The ends were fitted with insulation caps about 18 cm long. These caps were for the double purpose of insulation and sealing for the variation of air pressure both above and below atmospheric. A rotary air pump enabled the tube to be evacuated to about 5 cm of mercury in 5 minutes. Most changes of pressure could be made in a minute or two, but owing to numerous joints necessary for insulation purposes there was present some leakage, which necessitated a longer time to exhaust to the lowest pressure reached; and set the limit of about 5 cm as the minimum.

A small glass window was placed in the tube for making visual observations of the corona, but during most of the work the gold leaf electroscope was used for detecting the point at which corona begins. This method has been described in detail in the first of these papers[x] so no further description is necessary here. Fig. 1 shows the general arrangement of the apparatus. The beginning of corona is very sharply defined. A change of one per cent

[x] Whitehead: Trans. A.I.E.E XXIX, 1910, p.1159.

or less in the voltage will cause the time of complete discharge to change from about a half hour to five seconds. Any difference between the beginning of corona as observed by the eye and by the discharge of the electroscope is within this small error of observation.

The observations on the influence of temperature were made with a similar apparatus, except that the tube was in this case surrounded by a water jacket. Hand stirring of the water was found to be sufficient to keep the temperature of the air within the tube uniform to about two degrees. Only the smaller sizes of conductor could be used in this apparatus owing to spark over troubles occasioned by the reduced size of outer tube. The heating was done by gas burners and ice was used for getting reduced temperature.

Source of Power.

The power for all the experiments was drawn from a 10 KW., 100000 volt transformer. The transformer was operated by a motor generator set of 7.5 KW capacity, the generator field being excited by a storage battery, resulting in good voltage control. All experiments were made at a frequency of 60 cycles. The transformer is provided with a test coil giving 120 volts for 100000 volts on the high tension

terminals as computed from the ratio of primary and secondary turns. This test coil was used entirely in making measurements of the voltage. All determinations of ratio of maximum to mean effective voltage were also obtained from this coil.

4. Ratio of Maximum to Mean Effective Voltage.

For the purpose of checking the results this ratio was determined by two methods. The first makes use of the oscillograph, the second of a rotating contactor and the principle of the potentiometer.

The ratio was determined from the oscillograms by reading a number of ordinates, usually about 30 or 40 to a cycle. From these ordinates taken at equal distances the ratio of maximum to the square root of the mean square value was computed. The principal difficulty with this method is to obtain an oscillogram with lines sufficiently sharp and narrow.

The contactor method is indicated in Figure [illegible], the contact wheel being placed on the generator shaft. In the actual apparatus a handle was provided for readily shifting the point of contact. By reference to the galvanometer the contact can be shifted until the closure occurs on the peak of the wave. Then the slider on the rheostat is moved until the galvanometer indicates zero deflection.

The readings of the continuous and alternating current voltmeters are then taken. The ratio of their readings in volts is the ratio desired, the direct current voltmeter indicating the maximum voltage and the alternating current voltmeter the mean effective value.

The chief difficulty with this method is to keep the source of alternating voltage sufficiently steady during the time necessary for an observation. A damped galvanometer is required of fairly high sensibility. Only the relative calibration of the voltmeters is necessary since the ratio is all that is required. The alternating current voltmeter used was of the electrodynamometer type and it was compared with the direct current voltmeter by taking the mean of readings with reversed polarity.

Table 1, of which Fig. 3 is a plot gives the ratio of maximum to mean effective voltage for the various voltages on the test coil of the transformer used in the experiments. The values taken from the curve were used in making reductions of readings on critical intensity.

Figure 4 is a reproduction from a typical oscillogram.

Table 1.

$$\text{Ratio} = \frac{\text{Max. Voltage}}{\text{Mean eff. Voltage}}$$

Test Coil Volts	Contractor	Oscillograph	From Curve
4		1.395	1.400
7		1.420	1.420
10		1.450	1.440
15	1.451		1.440
20	1.459		1.445
25	1.436		1.445
30	1.429		1.445
35	1.438		1.445
50	1.444	1.446	1.440
60	1.421	1.430	1.440
75	1.452	1.427	1.440

5. Variation of Critical Intensity with Gas Pressure.

Fig. 5 shows the observed variation of critical corona voltage with pressure, while Fig. 6 shows the corresponding variation of critical intensity computed from the same observations. As mentioned before 9 conductors varying from .238 to .950 cm in diameter were used. Above 30 or 40 cm pressure the curves are nearly straight; the curvature being so slight as to be within the error of observation. They explain, therefore, the conclusion of the earlier paper that the relation between pressure and critical intensity is linear in this region.

The critical intensity is the electric field at the surface of the inner conductor. Its value is given by the formula:

$$X = \frac{dV}{dr} = \frac{E}{r \log \frac{R}{r}}$$

where X is the critical intensity, V the potential, r and R the radii of inner and outer conductors respectively. This may be shown as follows:

$$X = \frac{2\ e}{r}$$

for an infinitely long charged conductor where e is the charge per unit length. The capacity of concentric cylinders per unit length is given by the formula:

$$K = \frac{1}{2 \log \frac{R}{r}}$$

For a given difference of potential E the charge e is given by the equation:

$$e = \text{[illegible]} = \frac{E}{2 \log \frac{R}{r}}$$

$$X = \frac{2\,e}{r} = \frac{2}{r} \cdot \frac{E}{2 \log \frac{R}{r}} = \frac{E}{r \log \frac{R}{r}}$$

Tables 2 to 10 give a complete set of observations.

Several readings were taken at each pressure as shown in the readings. The pressure was determined by use of a gauge or manometer. This method gives, of course, only the difference of pressure between that in the tube and atmospheric. For this reason it was necessary to read the barometer to obtain the absolute pressure. The voltage was read by two Weston alternating current voltmeters of suitable ranges connected to the test coil of the transformer as has been stated before. In taking readings the electroscope was first charged and then the voltage gradually raised till the electroscope was suddenly discharged as shown by the fall of the gold leaf.

6. Empirical Formulae.

As stated before, Peek has given the formula

$$g = 31\delta \left(1 + \frac{0.308}{\sqrt{\delta r}}\right)$$

connecting the critical intensity g in kilo volts per cm with pressure, temperature and radius of conductor. Figure 8 shows curves for three sizes of conductor for the temperature 20°C. As indicated the circles are observed points while the full lines are plotted from the formula given above. It is seen that as the formula stands it does not meet these observations very closely, though it gives a curve of the correct general form. By suitable changes in the constants the formula

Table 2.

.238 cm Conductor.

Gauge Readings		Diff.	Barometer	Temp.	Pressure mm	Volts on test coil Read	Volts on test coil Corrected	Critical M.V. max.	Critical M.V. max. at 20°C	Critical Intensity M.V.
36	997	711	766	18.5	55	4.1				
46	997	11				4.0				
46	997	11				4.0	4.3	5.0	5.0	9.6
46	997	11				4.0				
36	997	11				4.0				
41	925	584				8.4				
40	26	86				.5				
40	26	86	766		180	.3	8.4	10.0	9.9	18.9
39	27	88				.3				
40	25	85				.4				
74	882	508				10.9				
75	82	7				11.0				
74	82	8	767		259	10.9	11.0	13.2	13.1	25.1
74	82	8				10.95				
74	81	7				10.95				
18	826	408				14.1				
18	26	08	767		358	4.1	14.2	17.1	17.0	32.5
17	27	10				4.1				
17	27	10				4.1				
66	762	296				17.2				
65	764	9				7.1				
66	62	6	767		470	7.2	17.4	20.9	20.8	39.8
66	62	6				7.3				
65	64	9				7.2				
05	709	204				19.7				
05	09	4	767		563	.7				
05	10	5				.6	20.0	24.1	23.9	45.7
05	09	4				.3				
43	657	114				22.2				
42	58	6				2.1				
42	58	6	768		653	2.0	22.2	26.7	26.5	50.6
42	57	5				2.1				
-	-	-				25.1				
-	-	-	768		768	5.0				
-	-	-				5.0	25.1	30.2	29.9	57.2
-	-	-				5.1				

Table 2 (continued)

.228 cm. Conductor.

uge Read-	ings	Diff.	Barom- eter	Temp.	Pres- sure mm	Volts on test coil Read	Cor- rected	Criti- cal K.V. max.	Criti- cal K.V. max. at 20°C	Critical Intens- ity K.V.
.9	532	97				27.5				
.8	34	4	768		863	7.5	27.6	33.2	32.9	62.9
.8	34	4				7.5				
.8	34	5				7.5				
5	466	209				30.2				
5	65	10	768		978	0.2				
5	65	10				0.4	30.4	36.6	36.3	69.4
5	66	09				0.2				
5	408	307				32.7				
4	08	6				2.7				
.4	09	5	768	16.9	1073	2.6	32.8	39.5	39.2	75.0
3	10	3				2.7				
4	09	5				2.8				

Table 5

.316 cm conductor

auge Read- ings		Diff.	Baro- meter	Temp.	Pres- sure mm	Volts on test coil Read	Volts on test coil Cor- rected	Criti- cal K.V. max.	Criti- cal K.V. max. at 20°C	Criti- cal In- tensity K.V.
88	1000	712	760	18.2	48	4.1				
88	00	712				4.2				
88	00	12				.2	4.5	5.3	5.3	8.0
88	00	12				.2				
88	00	12				.3				
16	958	642				7.1				
16	60	4				.1				
16	60	4				.0	7.2	8.5	8.5	13.1
15	60	5	760		116	6.9				
16	59	3				7.1				
49	915	566				10.2				
48	15	7				.2				
48	15	7	760		193	.2	10.3	12.3	12.3	18.9
48	16	8				.2				
48	15	7				.1				
562	910	549				10.9				
61	10	9				.7				
61	10	9	756	19.8	207	.7	10.9	13.0	13.0	20.0
61	10	9				.7				
61	10	9				.8				
431	846	415				15.6				
31	46	15				.6				
31	46	15	756		341	.6	15.7	18.9	18.9	[illegible]
31	46	15				.6				
483	799	316				1[illegible].9				
81	801	20				19.0				
85	797	12	756		441	19.0	19.3	[illegible]	[illegible]	[illegible]
84	98	14				19.1				
84	98	14				19.1				
550	760	250				22.0				
558	753	15				[illegible]				
57	53	16	756		556	[illegible]	22.4	27.0	[illegible]	[illegible]
36	54	18				2.5				
36	55	19				2.4				

Table 3 (continued)

.316 cm conductor

Gauge Readings		Diff.	Barometer	Temp.	Pressure mm	Volts on test coil Read	Volts on test coil Corrected	Critical K.V. max.	Critical K.V. max. at 20°C.	Critical Intensity K.V.
3	710	117				25.4				
2	10	18				.5				
1	11	20	756		638	.4	25.5	30.7	30.7	47.2
2	10	18				.4				
-	-	-				29.2				
-	-	-	756		756	9.9	29.4	35.4	35.4	54.3
-	-	-				9.[illegible]				
-	-	-				9.2				
5	597	158				34.0				
5	97	58				3.9	34.1	41.1	41.1	63.2
4	97	57	756		914	4.0				
4	97	57				3.9				
9	554	295				38.2				
0	55	95	756		1051	8.2	38.2	46.0	46.0	7[illegible]
0	55	95				8.2				
0	55	95				8.2				

Table 4

.400 cm conductor.

...ure Readings		Diff.	Barometer	Temp.	Pressure mm	Volts on test coil Read	Volts on test coil Corrected	Critical K.V. Max. Read ~~20°C~~	Critical K.V. Max. at 20°C	Critical Intensity K.V./cm.
8	999	711				4.4				
7	99	2				.3				
7	1000	3	760	18.1	48	.5	4.6	5.4	5.4	7.0
7	00	3				.3				
7	00	3				.3				
1	951	630				8.3				
1	52	31				.4				
0	52	32	760		129	.2	8.4	10.0	10.0	12.9
0	53	33				.2				
1	52	31				.3				
8	910	552				11.7				
8	09	1				.7				
8	09	1	757		206	.8	11.9	14.3	14.2	18.3
8	09	1				.8				
8	09	1				.8				
0	865	475				15.3				
0	65	5				.4				
0	65	5	757		282	.4	15.5	18.7	18.6	24.[illegible]
0	64	4				.4				
0	64	4				.4				
8	323	365				20.0				
7	24	7				20.0				
0	21	1	753	17.2	389	0.1	20.1	24.2	24.1	31.1
8	22	4				0.0				
8	762	234				25.[illegible]				
[illegible]	62	4				5.0				
8	62	4	753		519	4.9	25.0	30.1	30.0	38.7
7	62	5				4.7				
8	61	3				4.8				
7	713	126				28.6				
5	15	30				8.4				
7	13	26	753		626	8.5	28.6	34.4	34.2	44.1
7	13	26				8.5				
7	13	26				8.5				

Table 4 (continued)

.400 cm conductor

Gauge Readings		Diff.	Barometer	Temp.	Pressure mm	Volts on test coil Read	Volts on test coil Corrected	Critical K.V. Max. Read	Critical K.V. Max. at 20°C	Critical Intensity K.V./cm.
-	-	-				33.5				
-	-	-				3.1				
-	-	-	752		752	3.1	33.2	40.0	39.7	51.3
-	-	-				3.0				
-	-	-				3.0				
97	757	160				39.2				
97	57	60				9.4				
97	56	59	753		913	9.0	39.1	46.9	46.6	60.2
97	57	60				9.0				
56	871	335				44.7				
56	73	7				5.0				
56	73	7	753		1089	5.0	44.9	54.0	53.6	69.3
57	73	6				4.9				

Table 5.

.47[illegible] cm conductor.

uge Readings		Diff.	Barometer	Temp.	Pressure mm	Test Coil Volts Read	Test Coil Volts Corrected	Critical K.V. Max. Read	Critical K.V. Max. at 20° C.	Critical Intensity K.V./cm.
0	984	684	757	20.2	73	6.0				
0	84	4				.0				
0	84	4				.0	6.2	7.3	7.3	8.3
0	84	4				.0				
0	84	4				.0				
5	949	624				9.2				
5	49	4				.2				
4	49	5	757		134	.0	9.3	11.1	11.1	12.6
6	46	0				.2				
0	913	563				12.4				
0	12	2				.4				
0	13	3	757		194	.4	12.5	15.0	15.0	17.0
9	14	5				.3				
0	13	3				.4				
1	918	467				17.1				
0	19	69				16.9				
0	19	69				.9	17.2	20.7	20.5	23.2
1	17	68				7.1				
2	825	303				24.0				
2	25	3	749		446	4.2	24.1	29.1	28.8	32.6
1	25	4				4.1				
1	26	5				4.2				
4	741	157				30.2				
3	42	59	749		590	.1	30.2	36.4	36.0	40.8
3	43	60				.1				
3	42	59				.1				
	–	–				37.1				
	–	–				7.0				
	–	–	749		749	6.9	36.9	44.5	44.1	49.9
	–	–				6.7				
	–	–				6.7				
5	525	210				45.5				
5	25	10	749		958	45.2				
5	26	09				5.4	45.4	54.5	54.0	61.2
5	27	08				5.5				
2	485	297				49.5				
2	86	96				.1				
2	85	97	749		104[illegible]	.3	49.3	59.2	58.6	66.1
2	85	9[illegible]				.0				

Table 6.

.550 cm conductor.

Gauge Readings		Diff.	Barometer	Temp.	Pressure mm	Test Coil Volts Read	Test Coil Volts Corrected	Critical K.V. Max. Read	Critical K.V. Max. At 20° C.	Critical Intensity K.V./cm.
73	951	678	756	15.5	73	6.9				
72	51	9				7.0				
73	51	8				7.0	7.2	8.5	8.4	8.6
73	51	8				7.1				
21	962	541				14.9				
22	62	40			216	15.1	15.1	18.2	18.0	18.4
22	61	39				5.0				
22	61	39				5.1				
56	920	464				18.9				
55	20	5				.8	19.2	23.1	22.8	23.3
56	18	2			294	.8				
57	17	0				19.0				
56	17	1				9.0				
26	825	299				26.7				
27	24	7				6.8	26.8	32.3	31.9	32.6
27	25	8			457	6.6				
25	26	301				6.6				
39	741	152				33.4				
38	43	5				3.2				
38	42	4			601	3.5	33.4	40.2	39.7	40.6
36	44	8				3.2				
38	42	4				3.3				
–	–	–				40.3				
–	–	–			756	0.3	40.3	48.6	48.1	49.1
–	–	–				0.2				
–	–	–				0.2				
15	561	154				47.3				
15	60	5				7.4				
16	60	6			911	7.4	47.5	57.0	56.4	57.7
15	61	4				7.3				
46	514	232				50.8				
47	13	4			991	0.8	50.9	60.9	60.2	61.6
48	11	7				1.1				
48	11	7				0.8				
4[illegible]	12	6				0.6				

Table 7.

.638 cm conductor

Gauge Readings		Diff.	Barometer	Temp.	Pressure mm	Test Coil Volts Read	Test Coil Volts Corrected	Critical K.V. Max. Room	Critical K.V. Max. at 20° C	Critical Intensity K.V./cm
00	982	682	757	20.2	75	6.8				
00	82	2				.8	7.0	8.3	8.3	7.6
99	82	3				.8				
99	82	3				.85				
24	948	624				10.6				
24	47	3				.5				
24	47	3	757		134	.6	10.7	12.8	12.8	11.7
24	46	2				.6				
24	46	2				.7				
49	913	564				14.1				
49	13	4	757		193	.2	14.2	17.1	17.1	15.7
49	13	4				.1				
49	13	4				.1				
49	14	5				.2				
71	831	460				19.8				
71	31	60				.7				
72	31	59	748	16.4	288	.9	20.1	24.2	24.0	22.0
71	31	60				.8				
71	31	60				.8				
37	745	308				28.0				
35	46	11			441	7.9				
37	43	06	749			8.0	28.1	33.9	33.6	30.8
37	44	07				8.1				
36	45	09				8.0				
96	661	165				35.5				
96	61	65	749		585	5.4	35.4	42.7	42.3	38.8
97	60	63				5.4				
97	59	62				5.5				
–	–	–				43.4				
–	–	–	750			3.3	43.3	52.2	51.7	47.5
–	–	–				3.4				
–	–	–				3.2				
21	480	141				50.5				
22	80	2				.4				
21	81	0	750		891	.4	50.5	60.5	60.0	55.1
21	81	0				.4				
21	80	1				.1				
66	415	251				55.9				
66	15	1	750		1002	5.7				
68	13	5				6.0	[illegible]	[illegible]	[illegible]	61.1

Table 8.
.711 cm conductor.

auge Readings		Diff.	Barometer	Temp.	Pressure mm	Test Coil Volts Read	Test Coil Volts Corrected	Critical K.V. Max. Read ~~20°C~~	Critical K.V. Max. At 20°C	Critical Intensity K.V./cm
97	989	692	756	14.5	64	6.8				
97	89	2				.7				
97	89	2				.8	7.0	8.5	8.2	7.0
97	89	2				.9				
96	89	3				.9				
80	681	501				19.1				
79	82	03				.0				
81	78	497	756		256	.2	19.4	23.4	23.1	19.7
80	79	99				.1				
80	79	99				.2				
20	829	409				24.4				
20	29	9				4.4				
19	30	11			347	4.1	24.4	29.4	29.0	24.7
20	29	09				4.4				
20	29	09				4.4				
65	769	304				30.0				
65	69	4				0.0				
65	69	4			452	29.9	30.1	36.3	35.8	30.5
65	69	4				30.0				
64	69	5				0.0				
09	708	199				35.0				
08	09	201				5.5				
08	09	1			555	5.7	35.6	42.9	42.3	36.1
07	10	3				5.5				
08	09	1				5.6				
48	653	105				40.9				
48	53	5				0.9				
48	52	4			652	0.9	40.9	49.2	48.5	41.5
49	51	2				1.0				
48	53	5				0.6				
–	–	–				46.5				
–	–	–				6.5				
–	–	–			756	6.5	46.6	55.8	55.0	46.8
–	–	–				6.4				
–	–	–				6.5				
40	520	120				52.4				
40	20	20				2.5				
40	20	20			876	2.5	52.6	63.1	62.[illegible]	53.1
40	19	21				2.5				
82	458	224				57.6				
82	59	3				.6				
81	59	2			980	.9	57.9	69.5	68.5	58.4
83	57	6				[illegible]				
85	57	6				[illegible]				

Table 9.
.[illegible] cm. conductor.

Gauge Readings		Diff.	Barometer	Temp.	Pressure mm	Test Coil Volts		Critical K.V. Max.		Critical Intensity K.V./cm
						Read	Corrected	Read ~~20~~	at 20°C	
77	957	680				8.1		8.1		
77	57	80	759	18.0	79	.2	8.2	9.8	9.7	7.6
77	57	80				.2				
77	57	80				.2				
08	918	610				13.2				
08	18	10				.1				
08	18	10			149	.1	13.1	15.7	15.[illegible]	12.[illegible]
07	19	12				.0				
08	18	10				.2				
41	875	534				18.1				
41	75	4				.1				
41	75	4			225	.1	18.4	22.2	22.1	17.4
41	74	3				.2				
41	74	3				.2				
00	797	397				26.5				
00	96	6				6.7				
00	96	6			362	6.6	26.8	32.2	32.1	25.5
00	97	7				6.7				
99	98	9				6.4				
40	742	302				32.1				
41	40	299				2.1				
40	43	303			457	1.9	32.1	38.7	38.5	30.4
40	43	3				1.9				
40	43	3				1.9				
80	687	207				37.5				
80	88	8				.3				
79	88	9			552	.4	37.4	45.1	44.9	35.4
80	86	6				.5				
80	86	6				.[illegible]				
20	630	110				42.7				
20	30	0				2.7				
19	31	2			[illegible]	[illegible]	42.7	51.2	50.9	40.[illegible]
18	[illegible]	4				2.[illegible]				
20	29	09				2.7				
–	–	–				43.9				
–	–	–				3.9				
–	–	–			759	[illegible]	48.9	58.7	[illegible]	[illegible]
–	–	–				[illegible]				
–	–	–				[illegible]				
12	495	117				55.2				
12	[illegible]	6			[illegible]	.2	[illegible]	[illegible]	[illegible]	[illegible]
12	96	6				.[illegible]				

Table 10.

.950 cm conductor.

uge Read-ings		Diff.	Baro-meter	Temp.	Pres-sure mm	Test Coil Volts Read	Test Coil Volts Cor-rected	Critical K.V. Max. Read	At 20°C	Critical Intensity K.V./cm
1	983	682				7.8				
0	83	83				.7				
1	81	80	750	16.8	69	.7	7.9	9.3	9.2	6.4
1	81	80				.8				
0	82	82				.7				
5	937	602				14.2				
5	37	2	750		148	.1	14.2	17.1	17.0	11.9
5	37	2				.1				
0	882	502				22.1				
0	882	2				1.7				
0	82	2			249	1.7				
30	82	2	750			1.5	21.9	26.4	26.2	18.3
30	80	0				2.0				
9	80	1				1.8				
24	825	401				28.5				
24	24	0				8.2				
24	24	0	750		350	8.2	28.5	34.3	34.0	23.8
24	23	399				8.5				
24	23	99				8.5				
68	765	297				35.0				
67	66	9	750		463	5.0	35.0	42.2	41.9	29.3
68	65	7				5.0				
68	65	7				5.0				
38	738	250				37.9				
37	38	1				7.9				
37	38	1	760	21.2	510	8.1	38.0	45.6	45.7	31.9
38	36	48				8.1				
38	36	43				8.1				
–	–	–				53.1				
–	–	–				3.1				
–	–	–	758	20.8		3.2	53.3	63.9	64.0	44.7
–	–	–				3.2				
–	–	–				3.1				

is brought into close agreement.

Figure 9 is plotted from the formula:

$$g = 33.6\,\delta\left(1 + \frac{0.235}{\sqrt{\delta r}}\right) \qquad (2)$$

The circles show the observed points as before. It is seen that with the formula so changed it represents the observations about as closely as the readings can be taken. This formula gives zero voltage for zero pressure provided r has a value greater than zero which, of course, it has for any real case. As the present observations run only as low as 4 or 5 cm pressure, they furnish no test on this point. Investigations are now under way to determine what becomes of the corona at very low pressures.

If in equation 2 the value of δ at 76 cm pressure and temperature 20° be substituted the following formula is obtained:

$$g = 34 + \frac{11.2}{\sqrt{D}} \qquad (3)$$

This formula gives the variation of critical intensity with size of conductor at standard temperature and pressure. The curve in Fig. 7 is a plot from this equation while the circles are observed points. In Dr. Whitehead's work a formula of the same form but with different constants was given, namely:

$$g = 32 + \frac{13.4}{\sqrt{D}} \qquad (4)$$

The first constant of formula (4) is less than that of formula (3) while the second is greater, so the difference is largely one of curvature. What difference there is over the range of conductors observed is accounted for by a small discrepancy in the ratio of transformation of the transformers used in the earlier experiments and the present ones. It was found by trial in Dr. Whitehead's experiments that the indicated critical intensity with the 30000-volt transformer with which those experiments were conducted was 54 K. V. for a .345 cm conductor and 52.4 for the 100000-volt transformer which was used in the present set of experiments. These two differing values were obtained at the same time and with voltage from the same generator. Allowing for this discrepancy the present observations are brought into close agreement with the older values. As the purpose of this work is the investigation of the influence of density of gas on critical corona intensity, and as the above discrepancy does not affect the results relatively, its elimination has been left to later observations.

7. Variation of Critical Intensity with Temperature.

The curves of Fig. 10 show the variation of critical corona voltage with temperature corrected to the pressure 76 cm. Table 3 gives the data from which the curves were

plotted. The values computed are from the formula:

$$g = 33.6\,\delta\left(1 + \frac{\text{[illegible]}}{\sqrt{\delta r}}\right)$$

Table 3.

Diam. of Conductor	Temp. °C	Barometer	Test Coil Volts		Critical Intensity	
			Read	Corrected	Obs.	Comp.
.238	4.0	758	22.6	22.6	60.3	59.8
	24.3	760	21.5	21.5	57.5	56.6
	55.4	754	19.8	20.0	53.5	52.3
.315	3.7	758	26.4	26.4	57.6	56.8
	24.2	760	25.0	25.0	54.3	53.4
	50.8	754	23.1	23.3	50.7	50.0
.399	6.3	758	29.1	29.1	53.7	54.2
	24.2	760	28.1	28.1	51.6	51.3
	51.0	754	25.9	26.1	46.1	47.8

The diameter of tube used as outer conductor in these experiments was 10.5 cm. The curves in Fig. 9 are practically straight lines as the range of temperature is not great enough to bring out any curvature. The agreement with the revised Peek equation is also very close here.

8. Influence of Density of the Medium on Critical Intensity.

A simple calculation from the gas equation

$$pv = R\,T$$

shows that the pressure coefficient and temperature coefficient interpreted in terms of the change in volume of unit mass of gas are the same. In other words the critical corona intensity in air varies nearly as the density whether such change is produced by a change of pressure or temperature. This idea is implicitly stated in Peek's equation in his density factor . It must be remembered, however, that his definition gives only the relative density. With a view to the more definite measurement of density as the mass per unit volume we have made some interesting preliminary observations on the corona in a gas heavier than air.

In Fig. 11 are shown two curves of the variation of critical intensity with pressure, one in air and the other in a mixture of carbon dioxide and air, but containing about 90% by volume of the former. Owing to leakage of the tube it was not possible to fill it with pure CO_2.

It is seen that there is little change due to the presence of the CO_2 although its density is about 1.5 times

that of air. It appears then from this experiment that the variation of critical intensity does not, in fact, depend on the density, but is rather a function of the separation of the molecules of the gas, since according to the law of Avogadro the number of molecules in a given volume of gas is a function of the pressure and temperature only, and does not depend on the nature of the substance. The indication from these curves then is that the relation of the electric intensity and corona formation is found in the average separation of the molecules. This is in fact a principle tenet of the theory of secondary ionization or ionization by collision in explaining all forms of spark discharge in gases. A further study along this line may throw considerable light on some phases of the corona problem which are still obscure.

9. Comparison with Results on Sparking Potentials.

Figure 12 is reproduced from a paper by Watson on "The Dielectric Strength of Air"[5]. The curves show the variation of the sparking potential between spheres with variation of pressure. The pressures range from atmospheric

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[5] Jour. Inst. Elec. Engrs. Vol. 43, 190[illegible].

upward so that they are not directly comparable with the pressures in the present set of corona experiments. From the work of other observers, however, it is known that the curves extend down toward the zero until they reach the so called "critical pressure". Upon further reduction of pressure the curves turn sharply upward. These critical pressures vary with the length of spark gap, ranging from 3.0 to 0.3 mm for spark gaps of 1 to 10 mm, respectively[6].

It is seen by reference to the curves that their general shape is the same as for critical corona intensity. The chief question of interest in both cases is the departure from the linear law as the curvature is probably due to a common cause. By analogy with curves for sparking potentials it may be anticipated that the critical corona intensity may rise at very low pressures, in fact it is known that it is difficult to get the vacuum tube discharge at very high vacua.

The results obtained with corona in carbon dioxide were to be anticipated from Paschen's law. This law states that the sparking potential depends on the product of the pressure and the spark length. Curves plotted with products of pressure and spark length as abscissae and sparking po-

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6 Conduction of Elec. Through Gases. J. J. Thomson, 1906.

tentials as ordinates are nearly the same for air and carbon dioxide but differ considerably for hydrogen. No attempt was made to try hydrogen in the present set of experiments as the medium surrounding the conductor owing to the presence of some leakage of the tube which might have resulted in the production of an explosive mixture. It is interesting to note the simplicity of the corona apparatus as a method for studying the theory of gaseous conduction.

Discussion.

As most of the observed laws of corona formation are in accord with the theory of ionization by collision,a brief statement of some of the fundamental experiments and conclusions of that theory will not be out of place.

When two parallel conducting plates are connected to a source of potential difference and the gas between them ionized by X rays or radium, it is found that a current passes. This current increases at first as the potential difference is increased, but later attains a stationary value. No further increase of the current with increasing voltage is noted until a considerably higher voltage is reached when the current again increases rapidly with increasing voltage. The interpretation of this phenomenon is that the X rays produce ions at a definite rate so that the

current which can be produced by sweeping out all these ions has a limit. The stationary value of the current spoken of marks this limit. When, however, the voltage becomes sufficiently high the ions attain a velocity which enables them to produce new ones by collision with neutral atoms. This is known as ionization by collision or secondary ionization. This theory of ionization by collision accounts for the order of magnitude of the critical corona voltage which in the limiting case of plane surfaces is approximately 30 K.V. per cm. The mean free path of the electrons is about 6×10^{-5} cm at 76 cm pressure and 20°C as has been shown by Townsend and others. This is about 6 times the mean free path of the molecules of the gas. For the ordinary sizes of conductors the voltage over a mean free path of an electron is about 2 volts. This indicates that the critical intensity is that which gives the ionizing voltage of about 10 volts[7] in a distance of 5 times the mean free path, or in other words some of the electrons having a free path of 5 or more times the average, start the corona.

The ionization theory fails to show why the critical intensity varies with the size of conductor and why the variation of critical intensity with pressure does not

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[7] Bishop. Physical Review. Vol. [illegible], 1911.

follow a linear law. As has been frequently shown, the critical intensity rises quite rapidly as the size of conductor is reduced. The intensity in the gas falls away as $\frac{1}{r}$ where r is the distance from the center of the conductor, and from this it is seen that the intensity diminishes much more rapidly in the immediate neighborhood of a small conductor than a large one. Nevertheless the diminution in a distance of 5 or 10 mean free paths of an electron is negligibly small in any practical case.

The corona begins and ends at approximately the same voltage on the emf wave. This indicates that the rate of recombination of the ions is very great. It appears possible from this fact that the corona will not start until the intensity is high enough over some depth such as half a mm on account of the great amount of recombination which goes on in the neighboring space, where the intensity is too low.

Conclusions.

1. The critical corona forming electric intensity in air has been determined over the range of pressure 5 cm to 108 cm of mercury, for 9 sizes of round conductor of diameters from .13 to .95 cm.

2. A few observations on the influence of temperature within the range of 5° to 55° C. are also recorded.

3. The results are in substantial agreement with the empirical relation between electric intensity, pressure and temperature suggested by Peek.

4. Experiments with carbon dioxide indicate that the critical corona intensity is independent of the absolute density of the gas, but depends on the number and spacing of the molecules, in accord with the theory of secondary ionization.

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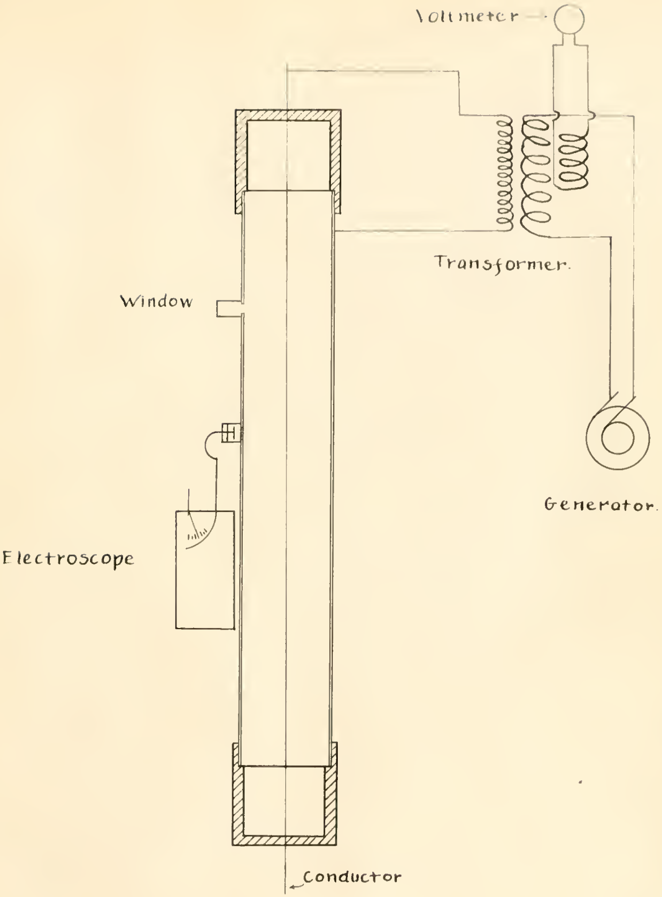
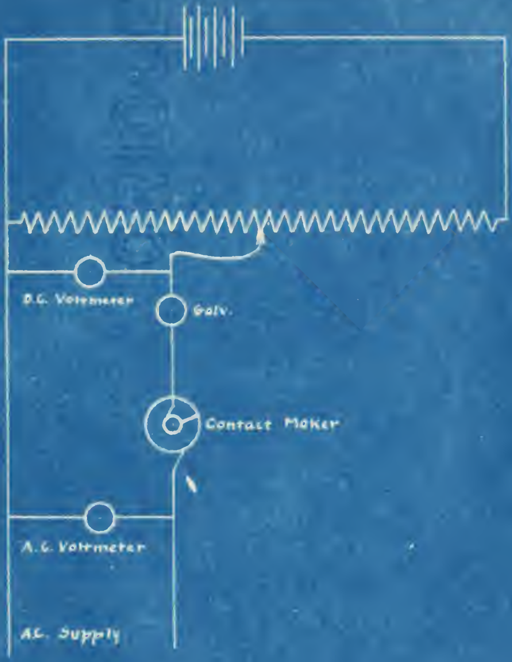


Corona Tube Apparatus.

Fig. 1.



Method of Measuring Ratio of Maximum to Mean Effective Voltage.

Fig. 2

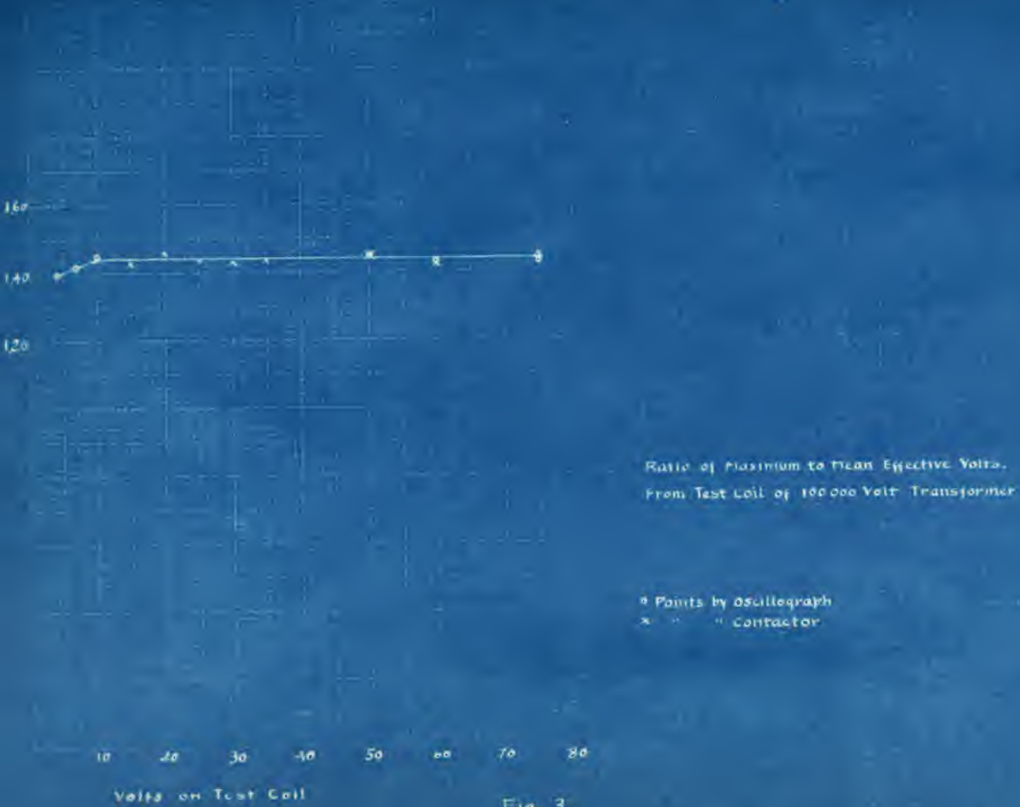
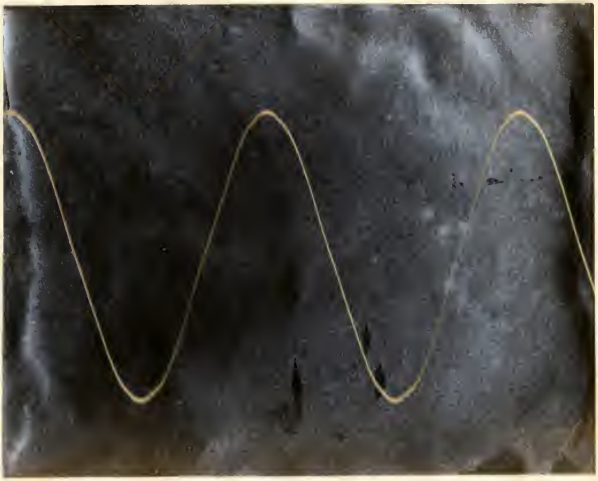
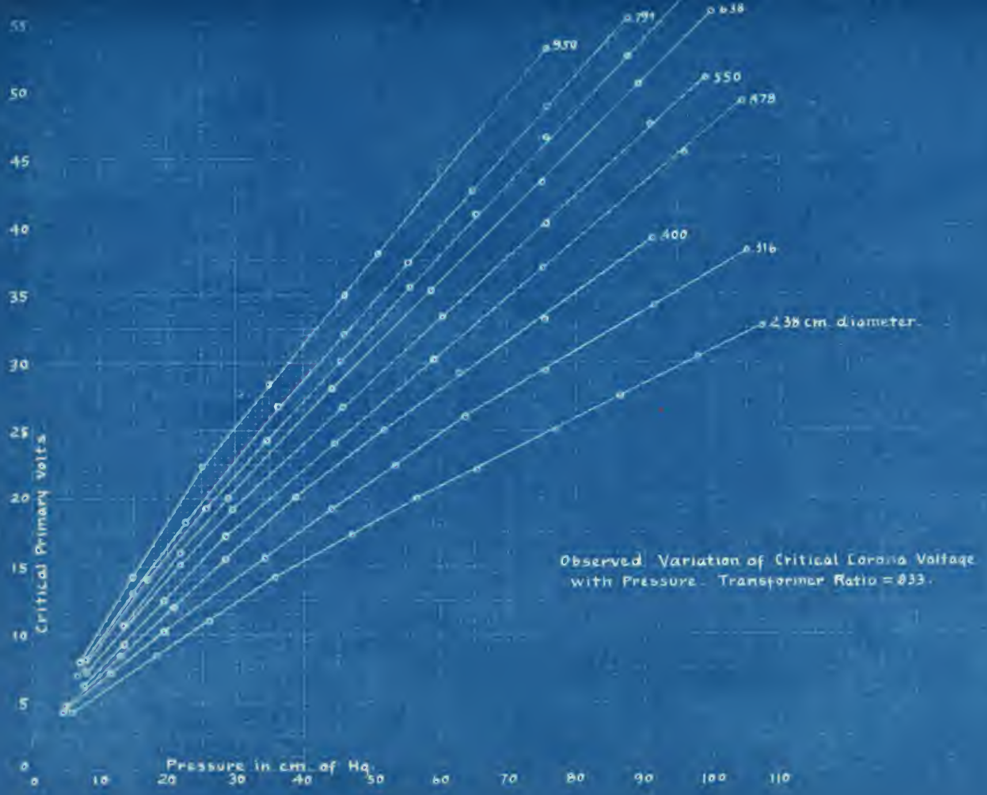

1.60
1.40
1.20
10
20
30
40
50
60
70
80
Volts on Test Coil
Ratio of Maximum to Mean Effective Volts.
From Test Coil of 100 000 Volt Transformer
o Points by Oscillograph
x " " Contactor

Fig. 3.



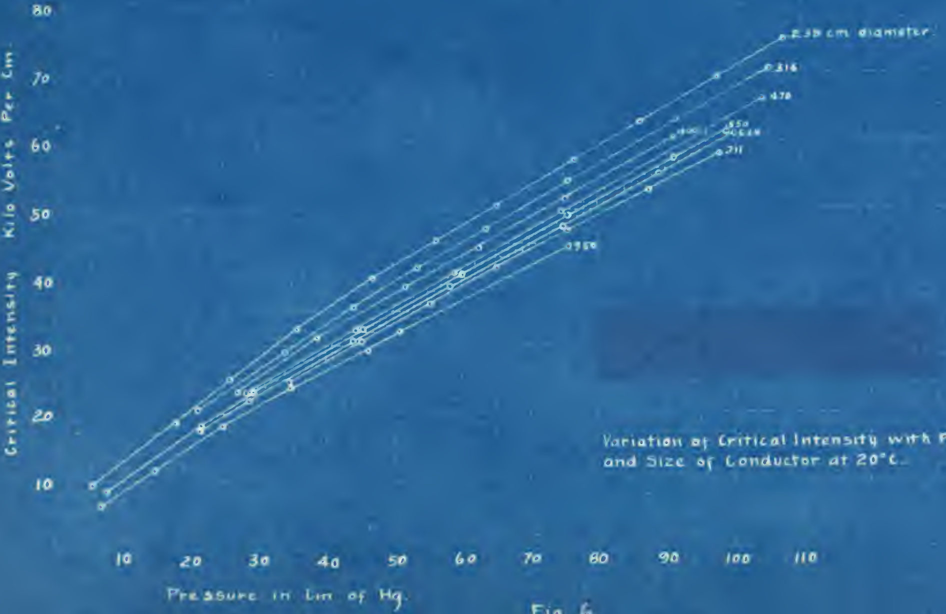
Oscillogram at 60 volts and 60 cycles.

Fig. 4.



Observed Variation of Critical Corona Voltage
with Pressure. Transformer Ratio = 833.
Critical Primary Volts
Pressure in cm. of Hg.
.950
.791
.638
.550
.478
.400
.316
.238 cm. diameter.
0
5
10
15
20
25
30
35
40
45
50
55
0
10
20
30
40
50
60
70
80
90
100
110

Fig 5



Variation of Critical Intensity with Pressure and Size of Conductor at 20°C.

Fig. 6

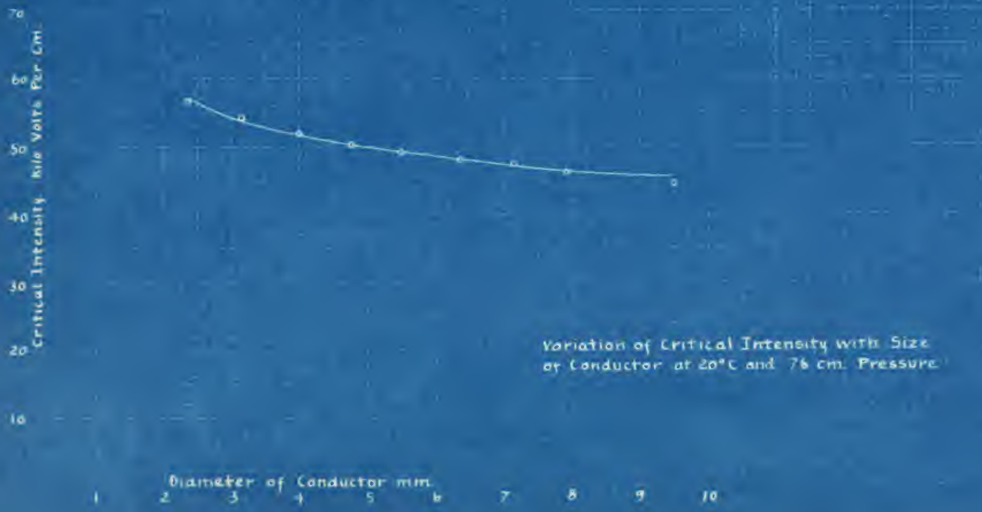
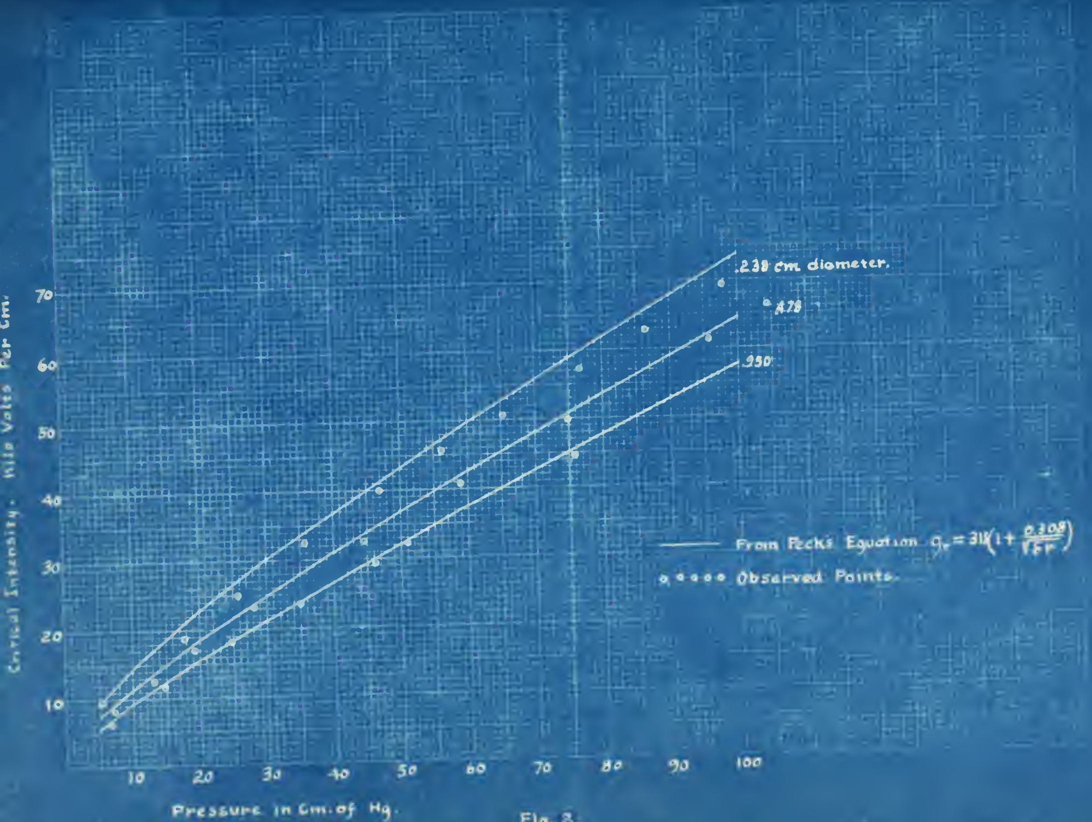

Critical Intensity Kilo Volts Per Cm.
70
60
50
40
30
20
10
Variation of Critical Intensity with Size
of Conductor at 20°C and 76 cm. Pressure
Diameter of Conductor mm.
1
2
3
4
5
6
7
8
9
10

Fig. 7



Critical Intensity. Kilo Volts Per Cm.
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
100
Pressure in Cm. of Hg.
.238 cm diameter.
.478
.950
From Peck's Equation $g_v = 31\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right)$
Observed Points.

Fig. 8.

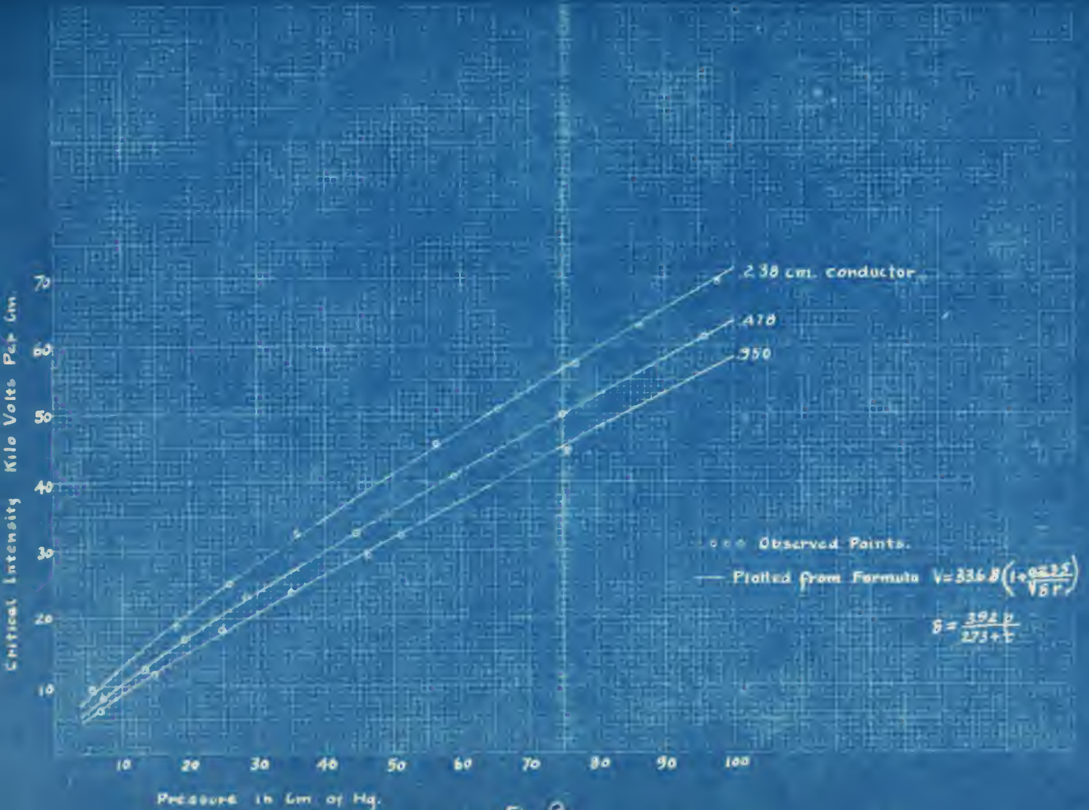
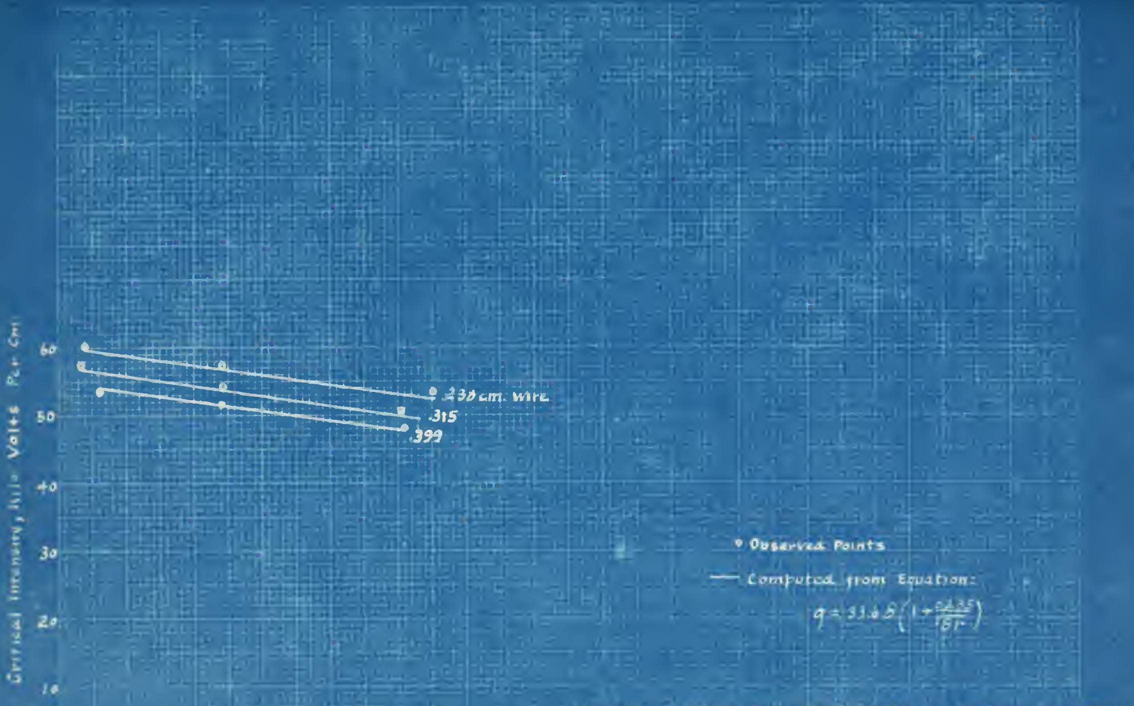
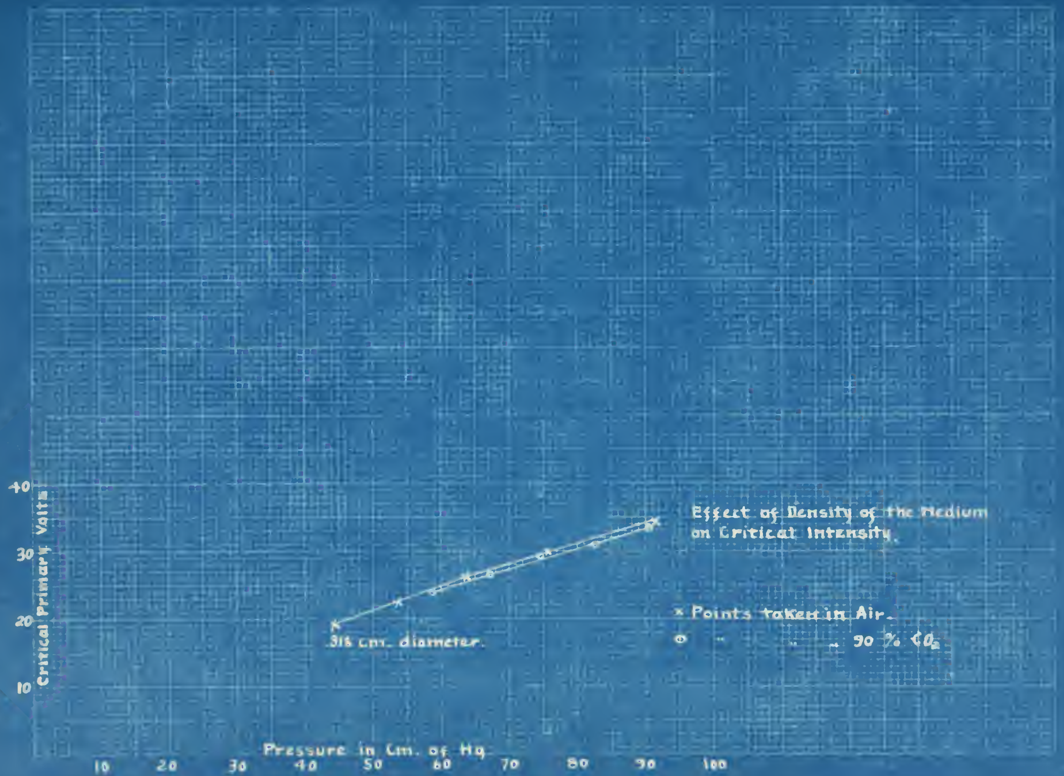

.238 cm. conductor.
.418
.950
○ ○ ○ Observed Points.
— Plotted from Formula $V = 33.6\,\delta\left(1+\frac{0.235}{\sqrt{\delta r}}\right)$
$\delta = \frac{3.92\,p}{273+t}$
Critical Intensity Kilo Volts Per Cm.
Pressure in Cm of Hg.
10
20
30
40
50
60
70
80
90
100

Fig. 9



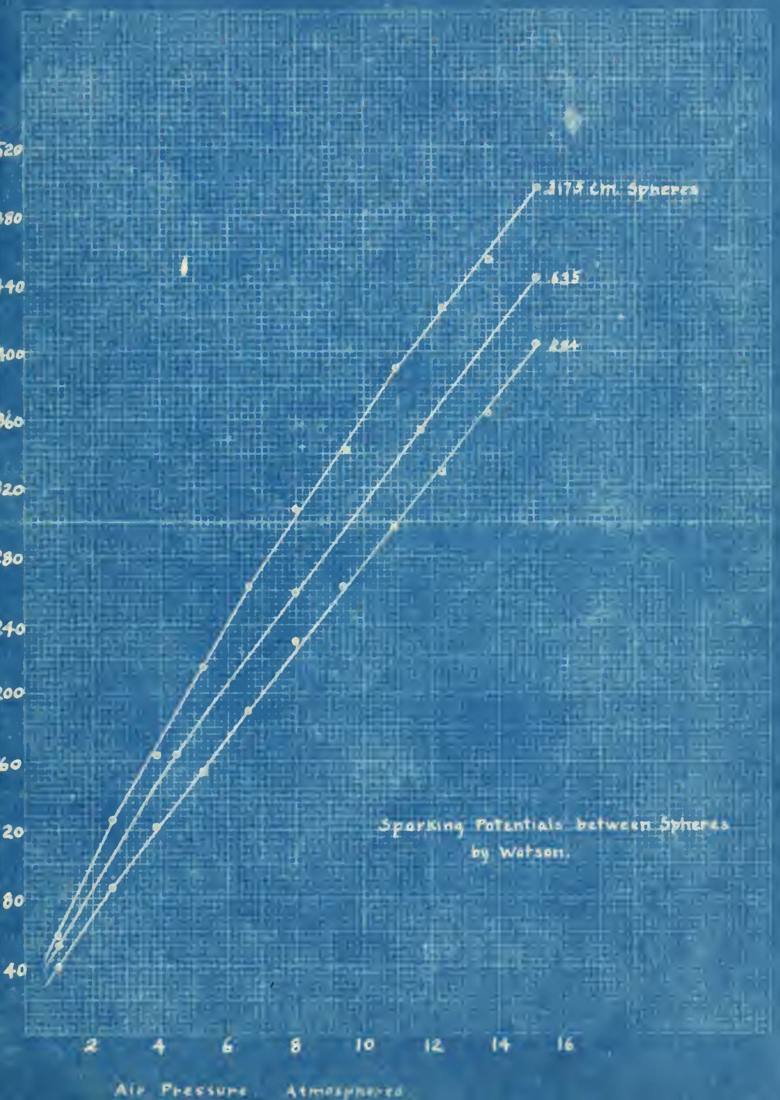
Variation of Critical Intensity With Temperature, at 76 cm. Pressure

Fig. 10



Effect of Density of the Medium
on Critical Intensity.
× Points taken in Air.
⊙ " " " 90 % CO_2
.318 cm. diameter.
Critical Primary Volts
10
20
30
40
Pressure in Cm. of Hg.
10
20
30
40
50
60
70
80
90
100

Fig. 11.


520
480
440
400
360
320
280
240
200
160
120
80
40
2
4
6
8
10
12
14
16
Air Pressure. Atmospheres.
Sparking Potentials between Spheres
by Watson.

Biographical Note.

Theodore Thornbur Fitch, son of Henry H., and Elizabeth Fitch was born in Sac County, Iowa, September 23, 1879. In 1898 he graduated from Sac City Institute, a college preparatory school. He spent the year of 1899-00 at the State University of Iowa, and the following scholastic year entered Iowa State College where he graduated in the course in Civil Engineering in 1903. He spent the year following in the U. S. Coast and Geodetic Survey. The following year, 1904-1905 he took up the study of Electrical Engineering at Iowa State College. Since 1906 he has been continuously on the staff of the Bureau of Standards at Washington, D. C., being now an Assistant Physicist. In 1910 he took up graduate work at Johns Hopkins University choosing Physics as principal subject and Mathematics and Astronomy as subordinate subjects. He took lectures under Professors Ames and Whitehead and Drs. Anderson, Cohen and Pfund. He also took a number of lecture courses given at the Bureau of Standards by Drs. Anderson, Pfund and Buckingham.